§7. Optimum Design Criterion of a Superconducting Magnet wound from Cable-in-conduit Conductors with Copper Matrix

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SUMMARY

Cable-in-conduit conductors (CICC) composed of a lot of superconducting strands with copper matrix are nowadays inclined to be mostly used for large superconducting dc or slow-ramp-rate pulsed magnets with a stored energy above several ten megajoules. An optimum design criterion of such a magnet is proposed. The criterion has two salient points as follows. 1) An overall current density of a magnet to be designed is determined temporarily based on a scaling law of stored energy due to large magnet production data and a theory. 2) The optimum critical current margin and optimum copper-superconductor ratio of a strand are obtained by the use of a stability theory of a tightly-wound superconducting magnet.

This optimum design criterion was applied to three pairs of poloidal field coils for the Large Helical Device. A pair of inner vertical coils with a stored energy of 161MJ has been delivered up to NIFS, and one of them is assembled into the SHE test facility. A pair of shaping field coils of 220MJ are now under construction in the factory. A pair of outer vertical coils of 600MJ are being designed in detail.

DESIGN PROCEDURE OF A MAGNET

The design procedure of a CICC superconducting magnet is as follows.

1) The electomotive force, the spatial conditions, the maximum magnetic field B_m(T), and the magnetic stored energy E(J) of the magnet are given.

2) The rated coil current I_{OP}(A) is determined tentatively based on a current scaling law

$$I_{OP} = K_1 E^{3/7} , \qquad (1)$$

where a coefficient $K_1 = 1\sim 20$.

3) The overall current density J(A/m^2) is determined generally on the basis of a current density scaling law

$$J = (E/E_1)^{-1/7} f(B_m) . \qquad (2)$$

Here, a function $f(B_m)$ is made from large magnet production data , and

$$f(B_m) = J_2 - (J_2 - J_1)(B_m / B_1) . \qquad (3)$$

In case of NbTi conductors, $E_1 = 120\times10^6$, $B_1 = 8$ T, $J_1 = 25\times10^6$, and $J_2 = 60\times10^6$.

4) The CICC dimensions are determined based on the rated coil current, coil protection, insulation, pressure drop through the conduit, conductor productivity, etc.

5) The dimensions of the superconducting strand and their numbers within the conduit are determined based on the strand production results.

6) The strand current density is

$$i = J / K_2 . \qquad (4)$$

Here, the strand space factor K_2 is a coefficient due to the conductor insulation specifications, conduit thickness, and void fraction.

6)-1. The thickness of the conduit is determined by the maximum strain and hoop stress due to magnetic forces.

6)-2. The radii of four inner corners of the conduit should be made smaller as possible in productivity in order to enhance the transverse stiffness and to make the helium paths at the corners.

7) The optimum critical current margin ι_{opt} and the optimum copper-superconductor ratio of a strand, m_{opt}, are obtained by the use of a stability theory of a tightly-wound superconducting magnet in the following.

$$\iota_{opt} = (j_C / i)^{1/2} \qquad (5)$$

$$m_{opt} = \iota_{opt} - 1. \qquad (6)$$

8) No insulation is done on surface of a strand, so that the current distribution at an initial charging of the magnet can be easily equalized and the normal current flowing in one strand at quenching can easily transfer to other neighboring strands.

9) The latter phenomenon gives another condition to the optimum critical current margin ι_{opt}. That is

$$\iota_{opt} > 2 . \qquad (7)$$

10) Superconducting filaments in the strand should be located more closely to the center as possible in productivity in order to reduce instability due to strand motion.

11) Cabling pitches of the superconducting bundle should be fabricated smaller as possible in productivity for the purpose of smaller strand motion and smaller AC losses.